Nuclear Reactor Safety

Vince A. Mousseau, T-3

There has been renewed interest in nuclear reactor power due to a variety of reasons. From a security standpoint it makes our nation less dependent on foreign countries. From an environmental point of view it mitigates the amount of greenhouse gasses being introduced into the atmosphere. Finally, from an economic point of view, the demand for energy is increasing worldwide and therefore the cost is growing steadily. Because of the increased regulation and cost of experimentation, development of modern nuclear reactors will rely more heavily on simulation and less on experimentation. This shift of emphasis to simulation will require an increase in the accuracy of nuclear reactor simulation codes. Because of this increased accuracy and decreased dependence on experimentation there is a natural transfer of technology that was developed for the Advanced Simulation and Computing (ASC) program to increase the efficiency and accuracy of these codes.

The current reactor simulators used in the U.S. were developed in the late 1970s to early 1980s. Because of the compute power available at that time many sacrifices had to be made to the accuracy of the simulation so that it would run in a reasonable amount of time. However, since there were large amounts of experimental data for these older reactors, the simulation codes mainly had to provide an answer that was close to the experimental data. In addition, older nuclear reactor designs depended heavily on large pumps to quickly cool the reactor in case of an incident.

Modern reactor designs have passive cooling systems that do not rely on pumps for safety. This however leads to safety transients that are much longer than their older reactor counterparts. This increase in transient simulation time requires a higher level of accuracy since the accumulation of small errors over a large number of time steps can lead to severe degradation of accuracy. However, because of the rapid growth in computer hardware, nonlinear equation solution algorithms, and software engineering, new simulation codes can be improved to meet the modern requirements of speed and accuracy.

Work has been progressing on development of numerical algorithms to obtain the accuracy [1] required for modern reactor safety applications. This approach obtains the accuracy through solving all of the nonlinear equations in a single implicitly balanced approach [2]. The efficiency of this algorithm comes from a hybrid approach based on combining the older algorithms, which are fast but inaccurate, with modern algorithms, that are accurate but computationally intensive [3]. This approach of using an older solution algorithm to accelerate a newer solution algorithm is called physics-based preconditioning. This preconditioner employed for these reactor safety simulations was originally developed on simplified equations in 2002 [4].

The difficulty in solving reactor safety transients is the spread in time scales of the different physics involved. When the reactor has not been SCRAM'ed (control rods inserted to stop the fission reaction), there is a very fast time scale associated with the neutron transport. The next fastest time scale deals with the mass, momentum, and energy exchange between the liquid and vapor phases of the cooling water, the next fastest time scale deals with the motion of the fluid, and the final slowest time scale deals with the conduction heat transfer in the metal of the reactor. These physical time scales can be different by many orders of magnitude.

The results presented are for a transient where the reactor is running at full power and then the heat addition due to nuclear fission is turned off (SCRAM). The transient then tracks the rate that the wall is cooled due to convection and phase change of the water. As the wall temperature cools, after the fission heat source has been turned off, the amount of steam produced goes down as an increase in the liquid volume fraction.

For the old solution algorithms, the physics of the heat conduction in the wall is operator split from the physics of the boiling water. In addition, the physics of heat conduction is additionally operator split into separate conduction solves in the "X" and "Y" directions. The physics of the boiling water is separated into a component from the speed of sound in the fluid and a component that corresponds to the velocity of the fluid. This breaking of the problem into smaller pieces was required to improve the speed of the simulation and to make the linear algebra solutions small enough to fit into the memory of a 1970s computer.

This splitting of the physics comes at a cost of accuracy and stability. Although these algorithms are fast and only require a small amount of computer memory, they must be run at time steps that are small. The modern algorithms, that solve the nonlinear system of equations in a single nonlinear solve, do not have the same problems with stability. Therefore, the only constraint on the time step is due to accuracy. However, since the implicitly balanced solution does not introduce any unphysical time scales due to splitting the physics, its accuracy constraints are determined by the physics of the simulation only.

Figure 1 shows these effects on a time step convergence study to examine the accuracy of the different algorithms. In this study the different algorithms are run for multiple time steps (on the X-axis) and their error (on the Y-axis) is plotted. The error is computed by taking the difference between an exact solution and the computed solution. The results from the old solution algorithms are shown with circles and the results from the modern algorithms are shown with squares. Three different transients are run for both the old and new algorithms. In the different transients the time scale of heat conduction was slowed down (by making the wall bigger) to lengthen the simulation time and spread the heat conduction time scale from the fluid time scales. The thicker lines (larger symbols) are for a larger spread in time scales and long transients; the thinner lines (smaller symbols) are for a smaller spread in time scales and shorter transients. A few observations can be made from this plot. First the old algorithm (circles) has a stability constraint at CFL = 1.0, therefore that is the largest time step that can be run. The new algorithm (squares) is always more accurate than the old algorithm and in addition, it can obtain high levels of accuracy at time steps much larger than the old algorithm's stability limit. The thick lines (and large symbols) represent the longer transients that will occur in the modern passive cooling systems.

The most difficult transients to analyze for nuclear reactor safety are incidents that occur when the reactor does not SCRAM (shut down). To analyze these transients the time scales are spread even farther by the inclusion of the fast neutron transport time scale. However, since the fission reaction rate is a function of both the wall temperature and the liquid volume fraction, the nonlinear coupling between all of the physics is actually increased. A fast and accurate solution method for this larger system will require improvements in the efficiency of the current algorithm as well as a more accurate algorithm for calculating the largest accurate time step for the simulation. In addition, since the transients for modern passive cooling systems are longer, additional work needs to be done to assess the long time accuracy of the different methods. This will ensure that the new reactor simulators will not accumulate error in these long transients.

For more information contact Vincent Mousseau at vmss@lanl.gov.

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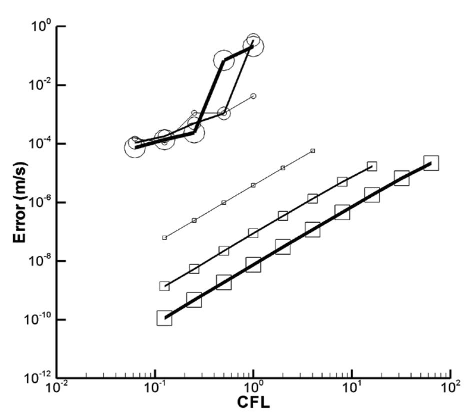

Fig. 1.
Accuracy comparisons between the old (circle) and new (square) methods.